Roddy, D. J., Pepin, R. O., and Merrill, R. B., editors
(1977) *Impact and Explosion Cratering*. Pergamon Press (New York), p. 163–181
Printed in the United States of America

Complex craters in alluvium

G. H. S. JONES

Defence Research Board Staff, Department of National Defence, Canada

Abstract—Experimental data are given on the morphology of several complex craters produced by the detonation of large TNT charges on the surface of alluvium at the Defence Research Establishment, Suffield, Canada. Primary attention is concentrated upon the Snowball Crater, the excavation of which is described in detail in terms of a diametral cross section along a system of displacement marker sand columns, and these displacement data are amplified by stratigraphic data. Comparable or supplementary data are given for several other explosive craters, particularly the Prairie Flat Crater.

It is shown that the craters produced in the highly compactible alluvium of the Suffield site exhibit a hierarchy which shows consistent pattern from craters with a simple, dome like central uplift to the final stage of a complex ringed crater with central uplift, marked radial, and concentric fissuring, a pseudo-volcanic extrusion of fluidized material along both radial and concentric structures, and terracing produced by late stage slumping. It is further shown that the ejecta blanket consists of a coherently overturned flap in which the original stratification is preserved, inverted, even when the stratum consist of fine, free flowing sand. The paper is essentially a summary of much more detailed individual reports which have only received limited circulation, to which reference is made in the text.

INTRODUCTION

STUDIES OF THE EFFECTS of TNT explosions with yields up to the equivalent of 1 KT nuclear were carried out over a period of many years at the Defence Research Establishment, Suffield, Canada. Many of the explosions produced complex craters exhibiting ringed structures, central uplift, and coherently overturned ejecta blankets.

Geological, seismic, and soil studies of the test sites have been given by (or cited by) Jones (1963, 1970, 1976). The present paper discusses craters produced on the Watching Hill Range, a site which consisted of horizontally stratified lacustrine silts, sands, clays, and gravels overlying glacial Till above a bedrock of softly indurated cretaceous shales and sandstones. The depth to bedrock was variable but close to 60 m, and a limited amount of free water appeared in boreholes at a depth of 10 m. However, many of the significant phenomena appear to be dependent upon the behaviour of the unsaturated but highly porous and compactible lacustrine sediments, as they were compressed to and beyond the saturation point.

The experimental data produced by the excavation of the central uplift crater called Snowball are summarized in this paper. Data from other trials, in particular the Prairie Flat ringed crater are given where these supplement the Snowball data. Full details of the excavations of both Snowball and Prairie Flat have been given by Jones (1970, 1976), both references being reports printed in limited numbers but now in the public domain.

105-03753/

Fig 1 Aerial view of Snowball Crater

The Snowball Crater was formed by the detonation of a 500 ton hemisphere of TNT on the surface, in July 1964, and Prairie Flat Crater by the detonation of a 500 ton sphere tangential to the surface on 8 August 1968. Some other trials are mentioned in the text.

Attention is drawn to Roddy (1968, 1969, 1976), which discuss many of the features of the Suffield craters using both the present writer's data and supplementary data collected by Roddy at the Suffield test site

The Snowball Crater before excavation

Figure 1 is an aerial photograph of the Snowball Crater the day after its formation. The ground surrounding the main crater was depressed to such an extent that the ejecta did not form an elevated rim. A large structural uplift

Fig. 2 Pseudo-volcanic sand cones aligned on radial fissure

occupied the approximate centre of the crater. From this uplift a gusher of sand-laden water rose to a height of about a metre with a stream diameter of about half a metre. Smaller gushers existed at various points around the inner slope of the crater and beyond the crater rim. By the second day the crater was partly filled with water and alluvium. The inundated areas beyond the rim, the circumferential cracks and the terracing show clearly in the photograph.

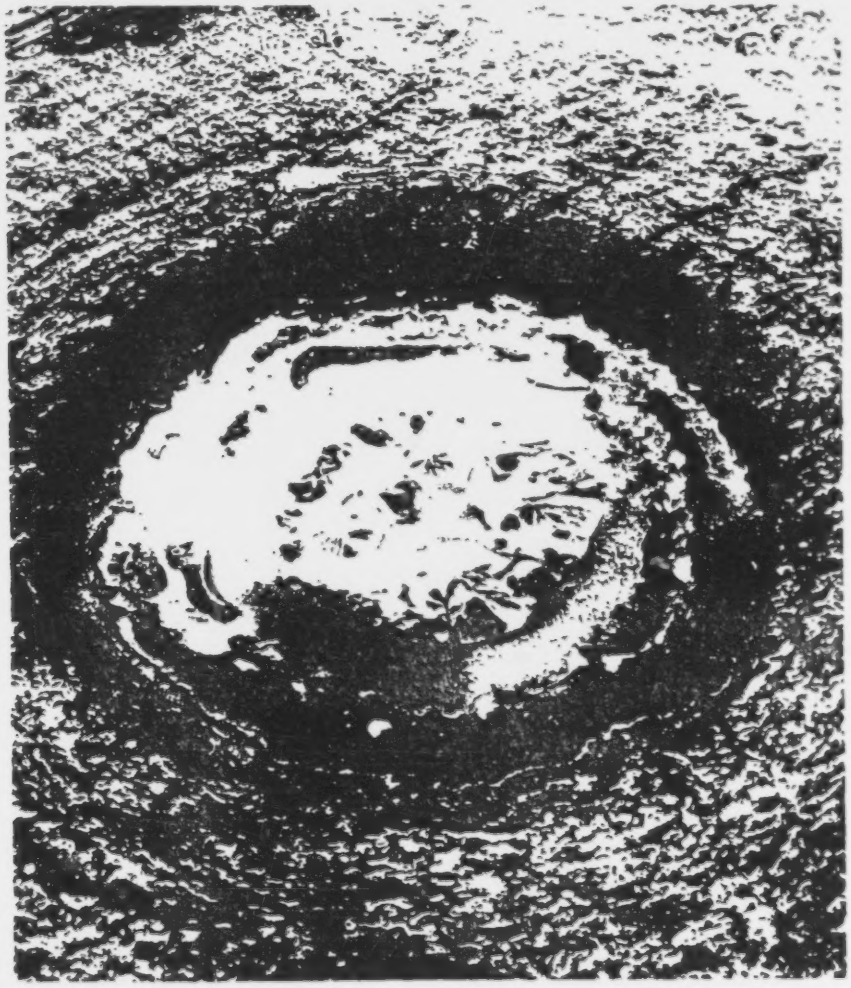

Fig. 3 Aerial view of Prairie Flat, with sand cones on concentric structures

Many of the water sources had the appearance shown in Fig. 2, which shows a chain of small cratered sand cones situated along a fissure radial to the main Snowball crater. On the Prairie Flat crater alignments of cones were located on concentric ring structures within the main crater as shown in Fig. 3.

Circumferential and radial fissures were detected on several of the Suffield craters. In the case of Snowball the fissures were open at the ground surface, even extending through the ejecta blanket, except in the limited areas where sand and water had risen to the surface and sealed the fissures as shown in Fig. 2. At depth, however, as shown in Fig. 4, these fissures were plugged with a

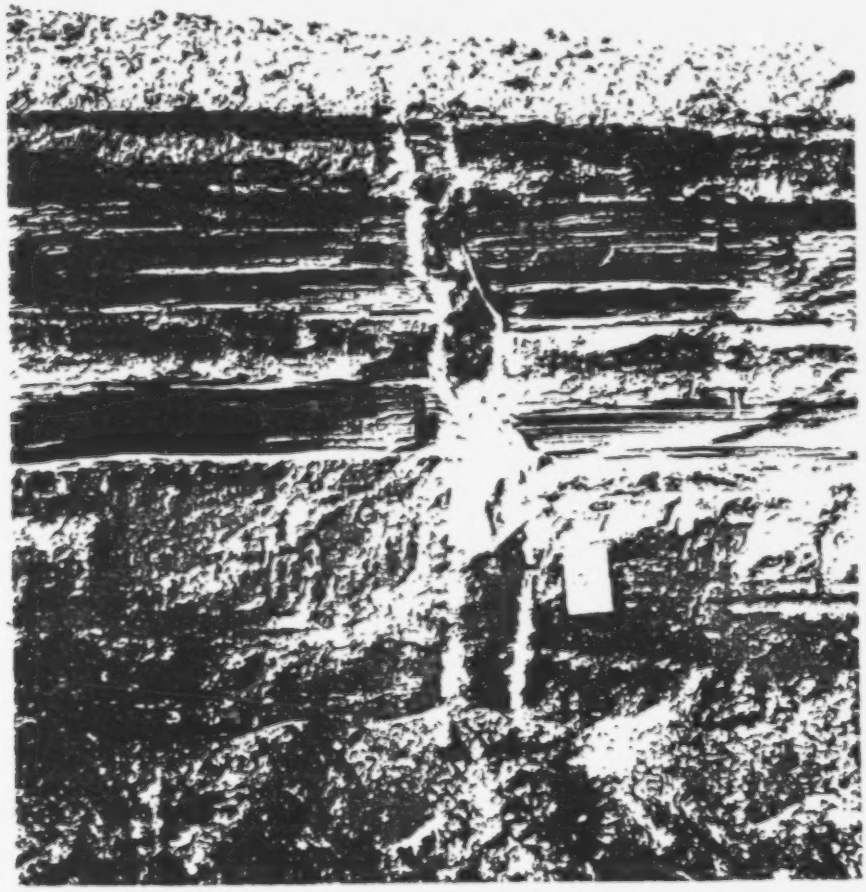

Fig. 4. Section through circumferential dyke on Snowball

close packed sand filling which penetrated the horizontal strata, including loosely packed sand strata, without spreading into "sills" along the stratification.

The sand column displacement markers

To obtain information on the origin of the ejecta blanket and to define the subsurface structural deformation the sand column technique of Perkins (1954) was modified as described by Diehl and Jones (1965) and used on the Suffield trials. In this technique numbered markers were placed at known intervals in vertical columns of mortar installed in boreholes. The pre- and post-shot locations of these columns and markers were surveyed to give information on the movement of the ground. It is stressed that the vector displacements do not indicate dynamic trajectories. Excavation of the sand columns, and the associated stratigraphical studies were completed during two consecutive summer seasons.

Section through Snowball Crater

Figures 5–9, taken together, depict a section through the Snowball Crater as determined by excavation along the main sand column line. In Fig. 5 we approach the crater from the south side, an area in which the pre-explosion stratigraphy was a series of horizontal lacustrine beds. At approximately 98 m (320 ft) from the centre of detonation (GZ) we encounter sand column S2 which exhibits significant movement in an outward and downward direction. This movement, of about 1 m at each marker location, would not have been recognized by stratigraphic study alone. Sand columns S3 and S4, show a progressive change in the nature of the residual displacement in the ground. Contrary to what might have been expected the residual displacements become less, rather than greater, as one approached the crater. The outward movement vanishes, but the vertical depression remains. This is clearly connected with the presence of the major circumferential crack at about 69 m (225 ft) from GZ

Figure 6 is the next section sequentially in towards GZ and shows the crater wall from the region of the circumferential crack to a point well within the crater proper. Sand columns S5 to S13 all show movement inwards toward the crater, and downward. The column S5, just within the circumferential crack, shows movement which is almost a mirror image of that associated with the column S4, just outside the crack. It indicates a residual movement which is little more than the necessary inward movement to allow the crack to open. The columns progressively nearer to the crater rim, however, show increasing inward and downward movement The stratigraphy in this area correlates with the columns and confirms the downwarping of the strata.

There were numerous sub-vertical cracks, some relatively local and others being part of circumferential systems of cracks. The dip of the upper layers increases as one approaches the rim of the crater, and the boundaries among the strata exhibit numerous examples of folding, minor slumping, and systems of

NORTH-SOUTH CAN LINE
STRATIGRAPHY & CAN VECTORS
Solid Lines Actual Surveyed Areas
Dashed Lines From Driving Samples
All Distances & Elevations in Short n Feet

Fig. 5. Snowball section—part A

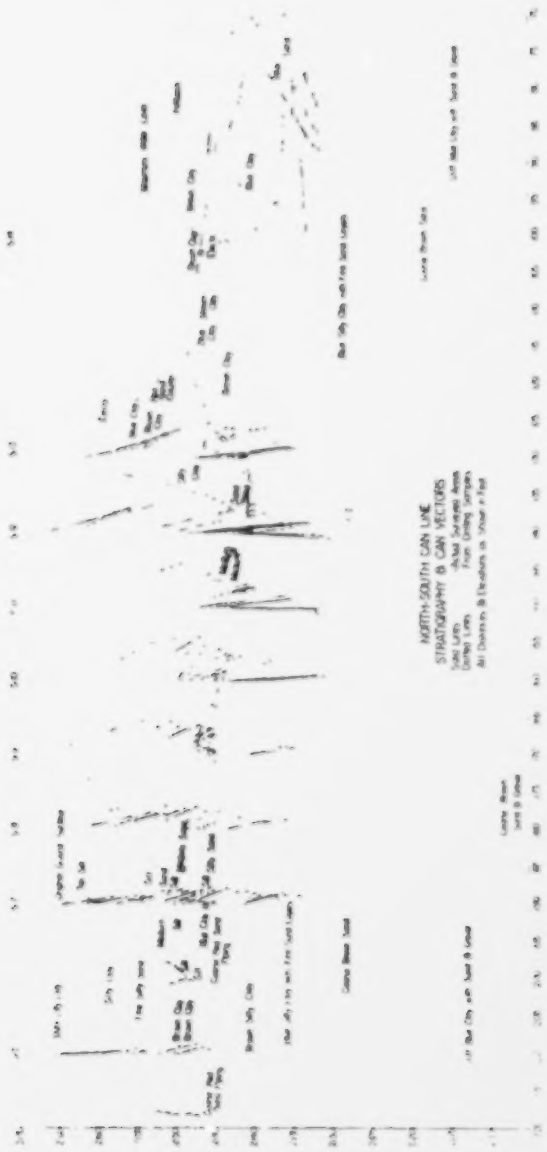

Fig. 6 Snowball section—Part B

Fig. 7. Snowball section—part C

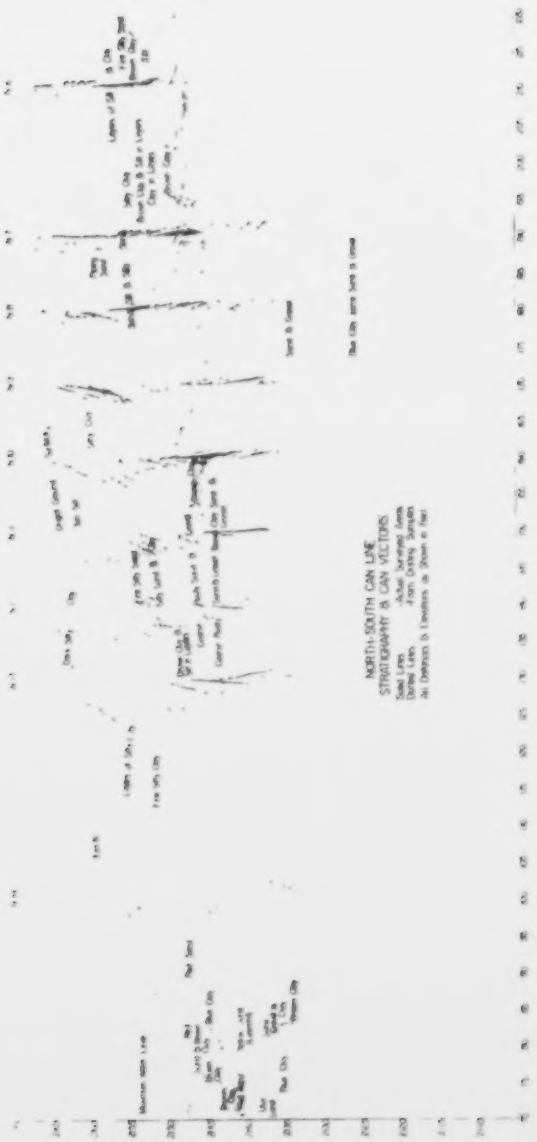

Fig. 8. Snowball section—part D

Fig. 9 Snowball section—part E

conjugate normal faults as would be expected in a structure resulting from a stretching and slumping of the material.

If Snowball had been the only crater of this type excavated one would probably interpret this downwarping of the strata as being entirely due to slumping within the circumferential crack system. However the other two 500 ton craters at Suffield, Prairie Flat and Dialpack show no evidence at all of slumping, but do exhibit marked downwarping of the strata in this region. In both the last named craters, residual movement as indicated by the sand columns was *outward* and downward, thus denying the slump mechanism. Thus the data from Snowball represent a late phase slumping of previously downwarped strata. Figure 6 shows data obtained by core drilling to deeper depths than could be excavated, and demonstrates the downwarping of the contact between the blue clays and a coarse brown sand layer. These strata, after downwarping in this region, then rise into a major circumferential ridge within the crater proper. This downwarp beneath the rim and the upward slope within the crater is entirely consistent with the data from the other trials.

Column S13 is roughly coincident with the position of maximum downwarp. The motion of the upper markers in this column, and also of the adjacent columns, show a tendency for the top of the column to overturn outwards, and the stratigraphy shows a coherent overturning of the strata in this region despite the completely incompetent nature of the sand and silt layers. Figure 10 is a photograph of this region of Snowball, while Fig. 11 is the equivalent region for Prairie Flat. The overturned strata may be traced continuously to the limit of the ejecta blanket.

Within the crater proper, just beyond the region of coherent overturning shown in Figs. 10 and 11, there is an arch concentric with the crater, in all of the 500 ton craters. In Snowball, this is not very evident, but is clearly revealed by the drilling data. The surface manifestation on Snowball appears to have been masked by the late phase slumping and the heavy deposit of sediment.

The deeper markers of column S14 indicate very large movement inwards towards the centre, almost horizontally at this location, while the upper markers suffer large outward and slightly upward movement into the hinge region of the ejecta flap consistent with a coherent overturning of the material. Immediately below the floor of the crater we see in Fig. 6 the final resting points of markers in sand columns originally in the central regions of the crater.

Figure 7 shows a section taken through the central region of the crater, including the uplifted central peak. Consider first the area between the positions of sand columns S15 and S16. We have commented above on the upper markers from column S15, moved outward into the overturned flap. We see that the deeper markers move inward, consistently with those of columns S13 and S14. Column S16 shows a similar pattern, but the combination of S15 and S14 movement in the upper regions confirm not only the existence of an overturned flap, but also demonstrate the formation of an anticlinal structure. This is confirmed by the drilling data from the deeper lying strata, which show the blue clay forced upward into an anticline at this location.

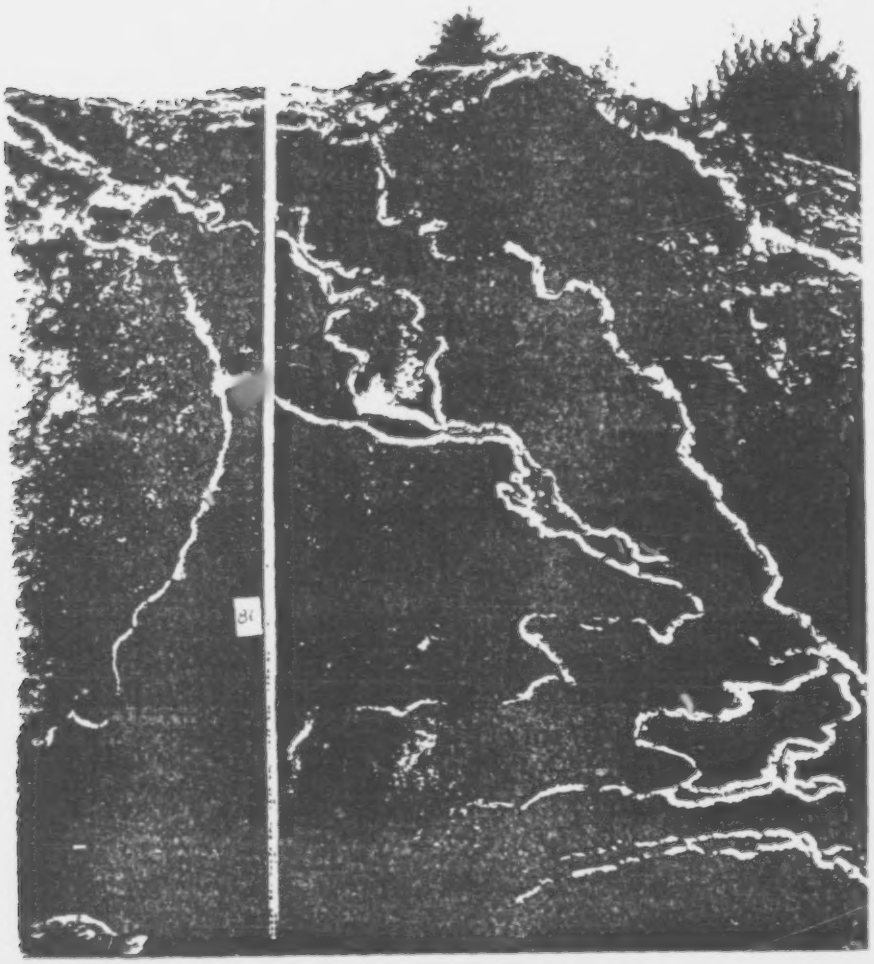

Fig. 10. Overturned hinge region of Snowball

The bottom series of markers from sand column S16 show the inward and upward displacement resulting in the formation of the central uplift structure. All the markers in column S17 confirm the formation of the structural uplift with the exception of the bottom four markers. The markers from the bottom four locations in the column were recovered in the anomalous position shown by the displacement vectors plotted in this figure. These vectors are quite inconsistent with the other displacement vectors, across which they pass. The markers for

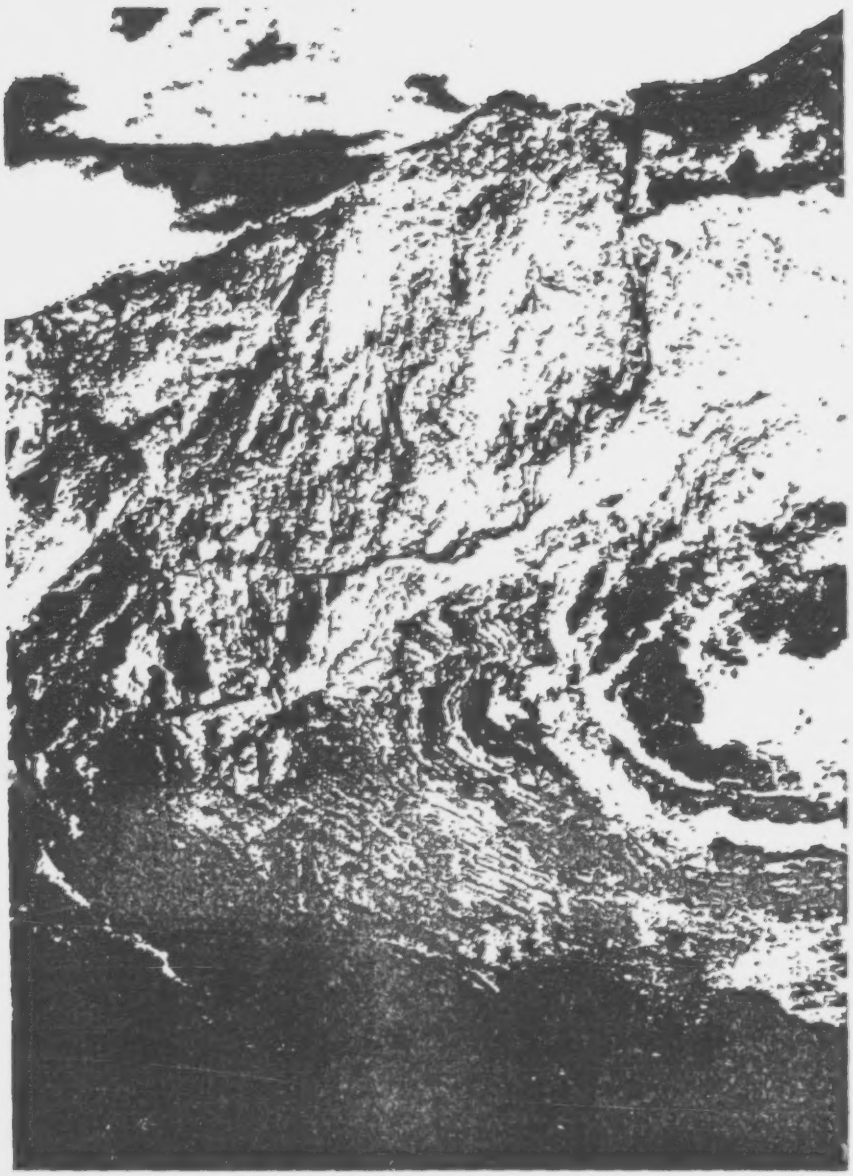

Fig. 11. Overturned hinge region of Prairie Flat.

these locations were probably carried to their final resting points by the high pressure flow of water, which was most concentrated in the region of the central uplift. At some early stage in the formation of the central structure, a zone of distension, coupled with very high water pressures and hydraulic fracturing, could exist in this region and free the markers from the columns, and allow them to become entrained in the subsequent water flow.

The central uplift structure was not placed symmetrically at the ground zero of the detonation, but rather was displaced towards the north. The asymmetry is pronounced in the displacement vectors from sand columns S18 and N18. Initially these two sand columns were positioned symmetrically south and north of the GZ position respectively. Upon excavation, however, the markers from the upper levels of both of these columns were found on the north side of the crater. The recovery of the upper markers from N18 in this location is to be expected. To recover the S18 markers in this area is, however, inexplicable in terms of homogeneous material. However, the GZ of this detonation was very close to a transition zone between the horizontal lacustrine sands and silts and a system of gravel beds (a shoal or delta deposit). This factor of asymmetry in the cratered material is the only explanation that can be offered for the northward displacement of the central uplift, and the markers from sand column S18. It is, perhaps relevant that the main water source was located on the south side of the central uplift, that is to say almost exactly at GZ. The area of recovery of the markers is in a synclinal trough around the central uplift, in the area of the deepest deposit of sediment. The displacement vectors for the lower markers in column N17 are symmetrically arrayed with those from column S17, a mirror image which indicates clearly the central uplift formation of the structure.

The central structure consisted mainly of uplifted blue clay, with a capping of yellow clay-silt. Through this uplifted mass ran many fissures, which became filled with waterborne sand from considerable depth. It is probable that the material of the central mound was uplifted sufficiently to produce a tensional stress condition. In such a situation one would anticipate tension fractures as actually found in the central mound filled with waterborne sand. Excavation confirmed this structure, and also showed that the upper layers of the mound had been altered by heat or pressure to a comparatively strong material. This material shattered in the tension phase of the movement, as demonstrated in Fig. 12. This regular disruption of the material was quite different from the drying and cracking which the material would exhibit after long exposure to the air.

Figure 13 is a close-up photograph of one of the early sections cut through the central uplift Attention is drawn to the massive up-domed blue clay (the relatively smooth bottom area of the photograph). The blocky material overlying this dome could, from this photograph, be thought to be "fall back" from the ejecta. This would definitely be a wrong interpretation as this material, as found *in situ*, was composed of large expanses of the yellow clay, essentially in conformable contact with the blue clay, but showing much greater disruption, evidence of a more frangible rather than plastic displacement. These massive "blocky" fragments of the yellow clay were not only conformably situated

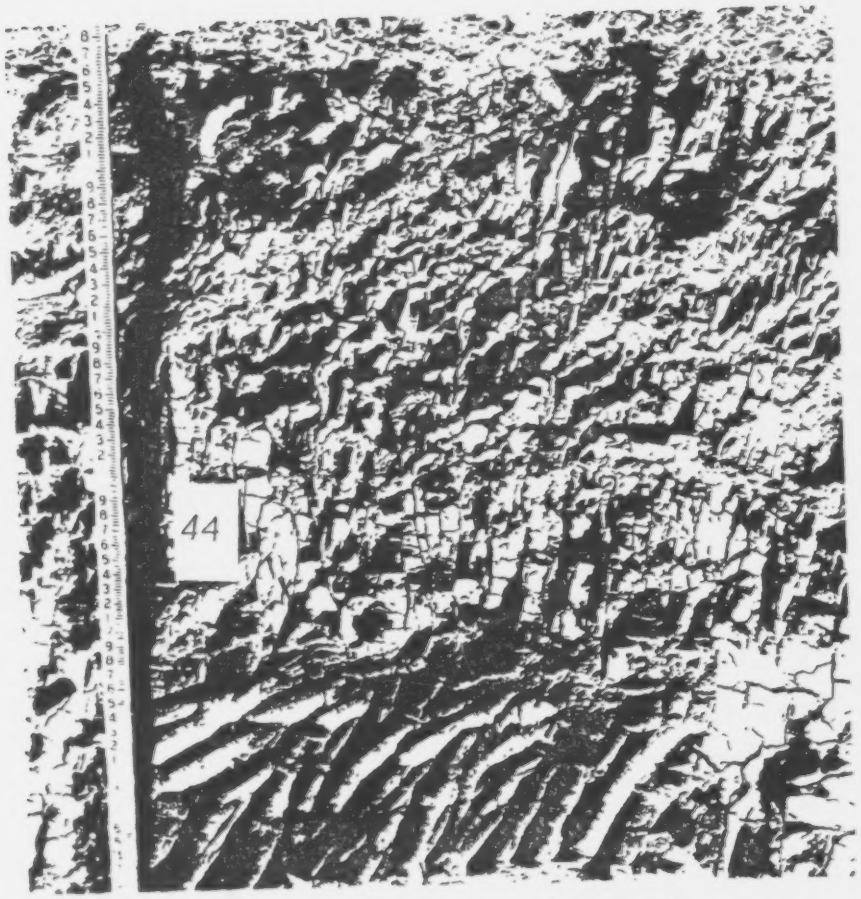

Fig 12. Tension fracturing of central uplift of Snowball.

above the blue clay but in some places the blue clay had actually flowed around the discrete blocks, completely encasing the blocks as large inclusions in the plastic blue clay. This is clearly visible in the photograph of Fig. 13, which also shows the presence of hydraulic fractures filled with sand.

Figure 14 shows the comparatively flat floor of the crater, formed by the great thickness of sedimentary infilling, overlying the thin layer of fall back material above the brecciated yellow clay which in turn overlies the plastic blue clay. The contact between the blue and yellow clays shows much relief, while the blue clay shows both included breccia of the yellow clay and some hydraulic fracturing.

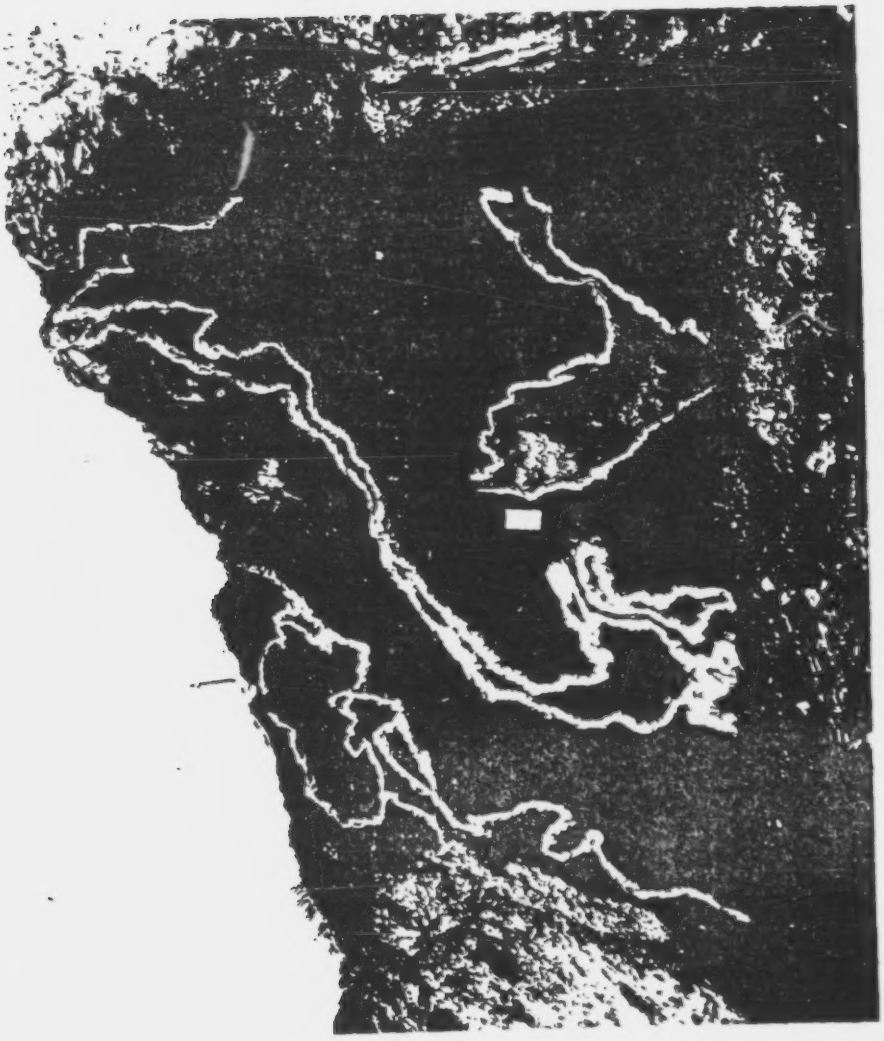

Fig. 13. A sectional view of part of the Snowball uplift

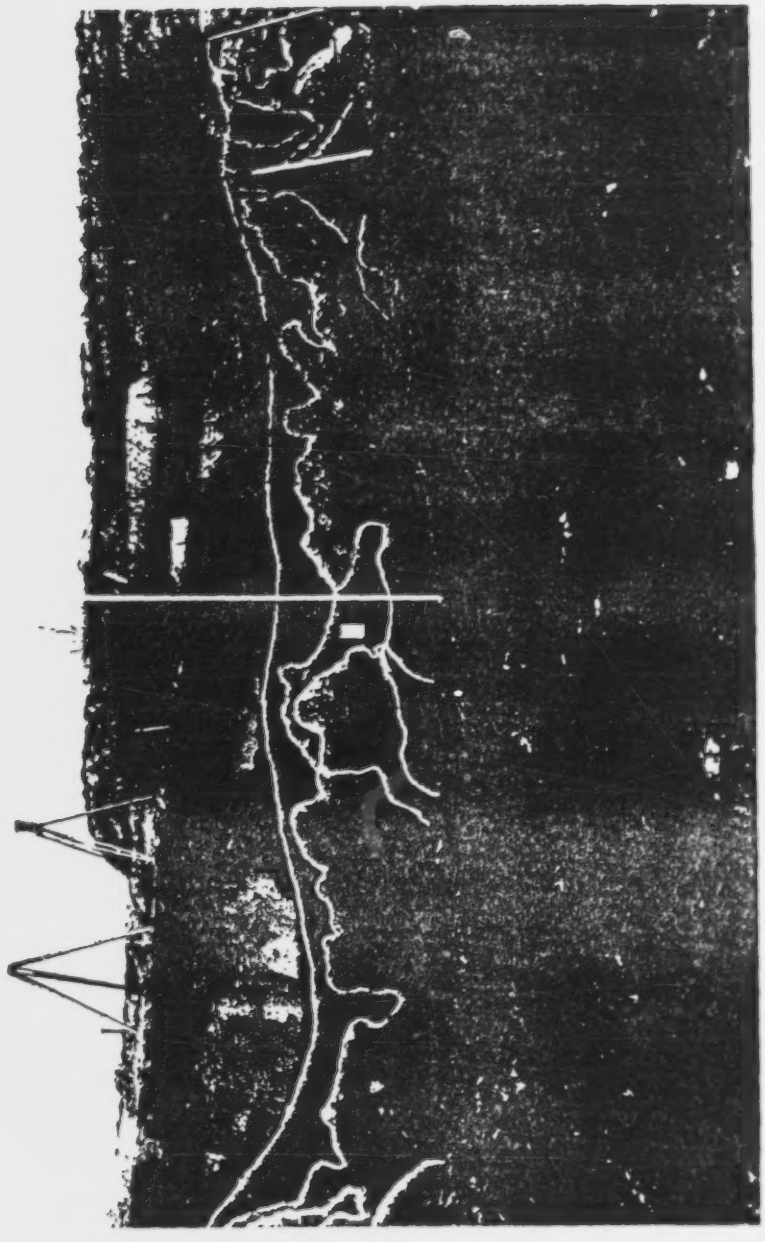

Fig. 14 Cross sectional view of part of the Snowball Crater floor.

Figure 8 is a section through the north rim of the crater. Movement of the markers in column N15 shows the outward and upward movement into the hinge of the overturned flap. The stratigraphy taken alone for this region would tend to indicate an uplifted crater rim, but the sand column markers prove that the final displacement was downward. All the data from this northern rim of the crater indicate that in this region the movement of the upper strata was controlled by the presence of gravel beds above the blue clay. The deeper strata, including the blue clay, are continuous across the crater. The stratigraphy and the upper markers of columns N13, N12, N11, N10, and N9 all show inward and downward movement, greatest near the rim and decreasing with distance outward from the rim. However, it is significant that in this wall of the crater the displacement shown by the deeper markers is consistently *outward* and down. Taken together with stratigraphic information it would appear that in this case the slumping was in the form of slippage at the boundary of the coarse delta deposit. In Prairie Flat and in the 100 ton Suffield 1961 Crater clear evidence exists of a low angle thrust in this region (Jones, 1970). Subsequent reverse slippage along a low angle thrust is not unreasonable.

In column N8, the displacement pattern is similar to that described above, but the transition between the slumping movement and the outward and downward movement is quite sharp, and located on an extension of the postulated low angle slip plane suggested above. Just beyond this column there is a deep circumferential fracture zone analogous to the fracture on the south side shown in Fig. 4, and the sand column N7 is intimately associated with this fracture. The markers show almost vertical slipping near the surface, and outward and downward movement corresponding with no inward slumping in the deeper layers. Column N6, beyond the fracture zone, shows no evidence of inward slumping but considerable outward and downward movement.

The deep lying clay layers on this northern side of the crater show no evidence of deformation. The indication is that the deep layers were to a large extent protected by the presence of the gravel. In Fig. 9 there is no visible displacement of the blue clay underlying the sand and gravel beds, but the upper layers show a gradual reduction of the shallow dip angle. Columns of markers N5, N3 and N2 show the continued presence of outward and downward residual displacement.

Conclusion

The data given in this paper (and in more detail in the cited reports) indicate that near surface explosions in the compactible sediments of the Suffield test site produce craters which are structurally consistent and are analogous to many planetary craters of the ringed or central uplift type.

The complex craters are not uniform in the overall visual surface manifestation, but do exhibit a consistent hierarchy as follows:

(a) A simple dome-like central uplift, as demonstrated by the 100 ton Distant Plain 6 tangent sphere explosion crater (Diehl *et al.*, 1968).

(b) A crater with central uplift, but with some extrusion of fluidized material from the central uplift, forming a single pseudo-volcanic cone on top of the uplift. This is illustrated by the 100 ton Suffield 1961 Crater (Jones, 1976).

(c) A crater with internal ring structures on the crater floor, with pseudo-volcanic cones superimposed on the ring structures, as illustrated by Prairie Flat (see Fig. 3 of this paper).

(d) A crater with a dominant central uplift, with a depressed rim structure, evident radial and circumferential fissuring both internal and external to the main crater, and pseudo-volcanic cones both internal and external to the main crater. The final stage of such craters includes slumping of the crater walls to form internal terracing, and to some extent masking the internal ring structure. This stage is typified by the Snowball crater, discussed in detail in this paper.

In all the observed central uplift craters the ejecta blanket consisted of a coherently overturned, stratigraphically inverted expression of the pre-existing stratigraphy. In the blanket, strata could be traced from the undisturbed position, through a hinge region under the rim, and continuously through the ejecta blanket. In the ejecta the strata, after inversion, suffer radial thinning, but they retained precisely their relative positions even when the stratum consisted of a fine, free flowing sand. This overturning is clearly *not* due to sequential fall-out of the ejected material, but is a coherent roll-back of the strata.

Even after removal of the ejecta blanket (by excavation or erosion) the existence of the inverted stratigraphy is evidenced by the "hinge region" in which strata rotate through the vertical. Associated with this hinge region there were many examples of small drape folds and block faulting.

All the Suffield craters exhibit circumferential and radial fracturing of the ground surrounding the main crater. In some cases these fractures are accentuated by the injection of fluidized material (water borne sand at Suffield). The phenomenon associated with the circumferential fissures internal and external to the main crater were tracable at depth in the form of ring dykes which penetrate the country rock without spreading into sills at the contact with even incompetent strata. In addition to the ring dykes, there was an irregular injection of fluidized material due to a form of hydraulic fracturing.

The material of the central uplift may show signs of tension fracturing, with or without the injection of fluidized material.

There may be low angle thrust faulting included beneath the coherently overturned blanket particularly in the hinge region below the rim.

The ejecta blanket may include fused material deriving from the surface materials (for details, see Jones, 1976).

The floor of the crater may be covered by a mantle of fluidized material deriving from locations deep within the structure. In extreme cases, as illustrated by Snowball, regions external to the crater may be covered locally by similar beds of ejected fluidized material. These simulate in relative position the

"magmatic" material extruded in planetary counterparts, though at Suffield the deposits were sediments. However, they must not be confused with the sedimentary beds which are a feature of terrestrial astroblemes and fossil craters. Such beds would have developed at Suffield in due co e if the craters had not been excavated, and would have overlain the "magma ." deposits.

Acknowledgments—Permission to publish this paper, and to distribute the full report (Jones, 1976) to the delegates to the Symposium on Planetary Cratering Mechanics held at Flagstaff, Arizona was granted by the Department of National Defence, Canada

Financial support and much encouragement for part of this work provided by the Defence Atomic Support Agency of the United States is gratefully acknowledged by the author

References

Diehl, C H H and Jones, G H S 1965. A tracer technique for cratering studies. *J Geophys Res* **70**, 305–309.

Diehl, C H H , Pinnel, J , and Jones, G H S. 1968. *Crater and Ejecta Studies on Distant Plain 6*. Suffield Tech. Note 208.

Jones, G. H S 1963 *Strong Motion Seismic Effects of the Suffield Explosions* Univ of Alberta PhD thesis (and as Suffield Report 208)

Jones, G H S. 1970. *Prairie Flat Crater and Ejecta Study*. DASA Report POR 2115 (WT 2115)

Jones, G H. S 1976. *The Morphology of Central Uplift Craters*. Suffield Report 281

Perkins, B 1954. A new technique for studying crater phenomena. Ballistic Research Labs Tech Note 880

Roddy, D J 1968. The Flynn Creek Crater, Tennessee. *Shock Metamorphism of Natural Materials*. Mono Book Corp

Roddy, D. J 1969. Geological Survey Activities. *Operation Prairie Flat Prelim Rep* 1, DASA 2228–1

Roddy, D J 1976. High Explosive Cratering Analogs for Bowl-shaped, Central Uplift, and Multi-Ring Craters *Proc Lunar Sci Conf 7th*, p 3027–3056

Defence Research and Development Canada | Recherche et développement pour la défense Canada

Canada

Français | Contact Us | Help | Search | Canada.ca

Home | Defence R&D Canada | Defence Site

Browse Indexes

Titles

Authors

Descriptors

Corporate Authors

Corporate Acronyms

Report Numbers

Search Database

Summary

It is recommended you search "Authors" and "Corporate Authors" on their respective "Browse" pages.

Click here if you are having problems displaying text (ie text is too big, or too small) or page appears to be jumbled.

Prior Top **Document:** 1 of 1 Bottom Next

Click here to Order

Click here to Download

TITLE:(U) COMPLEX CRATERS IN ALLUVIUM

PERSONAL AUTHOR: Jones, G.H.S.; Roddy, D.J.; Pepin, R.O.; Merrill, R.B.

CORPORATE AUTHOR: Defence Research Board, Ottawa ONT (CAN)

ABSTRACT: (U) Experimental data are given on the morphology of several complex craters produced by the detonation of large TNT charges on the surface of alluvium at the Defence Research Establishment, Suffield, Canada. Primary attention is concentrated upon the Snowball Crater, the excavation of which is described in detail in terms of a diametral cross section along a system of displacement marker sand columns, and these displacement data are amplified by stratigraphic data. Comparable or supplementary data are given for several other explosive craters, particularly the Prairie Flat Crater. TRUNCATED

DESCRIPTORS: (U) Craters;Alluvium;Trinitrotoluene;Excavation;Cratering;Cracks;Soils;Nitroaryl compounds;Nitrobenzenes;Nitro compounds

REPORT DATE: 01 Jan 1977 **NUMBER OF PAGES :** 23p

Reprints: Impact and Explosion Cratering, 1977, p 163-183

DRDKIM N°: 78-01466 **CANDIS N°:** 82167 **Format(s):**Hardcopy;Document Image stored on Optical Disk

Date modified: 2003-04-17

Important Notices